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BRIEF REPORTS

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Exclusive photonuclear reactions and asymptotic scaling

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Recent measurements of electron-deuteron elastic scattering at high momentum transfer have placed an empirical lower limit on the momentum transfer for the onset of asymptotic scaling. The implications that this limit has for the ^{2}H$(\gamma,p)n$, ^{2}H$(\gamma,d)\pi^0$, and ^{3}He(γ,d)H reactions will be discussed.

It is widely believed that asymptotic scaling in hadronic reactions occurs when the reaction cross sections obey the power law dependence of the constituent counting rules.[1] With this operational definition, asymptotic scaling appears to occur in high-energy proton-proton elastic scattering[2] and photopion production[3] from the proton. In addition, electron elastic scattering cross sections for the nucleons[4] and that deduced for the pion at high momentum transfer appear to obey the constituent counting rules. Although there is some debate[5] about the validity of perturbative QCD in these cases, there is a consensus that QCD is essential to explain these simplest hadronic reactions. However, for nuclear reactions, the meson exchange model has met with considerable success, and since it is unlikely that the quarks in a nucleus are deconfined from the hadrons, it is not widely believed that QCD is necessary to describe nuclear reactions or that asymptotic scaling should be observed. In fact, by retaining only a leading-order Feynman diagram in a hadronic model of the nucleus, it is possible[6] to produce the asymptotic scaling behavior for the $\gamma d \rightarrow pn$ reaction.

Indeed, the most intensively studied nuclear process, electron-deuteron elastic scattering, indicates that the cross section[7,8] at the highest momentum transfer does not scale. The cross section

$$\sigma(Q^2)=\sigma_M[A(Q^2)+B(Q^2)\tan^2(\theta/2)]$$

can be described by two components, $A(Q^2)$ which depends primarily upon the electric form factors of the deuteron, and $B(Q^2)$ which depends only on the magnetic form factor. The lack of asymptotic scaling at presently attainable values of momentum transfer Q is illustrated in the upper panel of Fig. 1. Since one would expect the cross section to fall off as $\sigma/\sigma_M \sim 1/Q^{20}$ according to the constituent counting rules, then the quantity $(\sigma/\sigma_M)Q^{20}$ should approach a constant value in the scaling region. Clearly, this could only occur at $Q^2>4$ (GeV$/c)^2$. This argument is strengthened by noting that the recent measurements[8] of $B(Q^2)$, shown in the lower panel of Fig. 1, exhibit a minimum near $Q^2=2$ (GeV$/c)^2$. The presence of this minimum in the form factor is characteristic of a two-nucleon description of the deuteron. Furthermore, the curves shown in Fig. 1 are in good agreement with these data and represent a calculation[9] based only on the two-nucleon model of the deuteron. Thus, it seems evident that one should not expect asymptotic scaling to occur in *e-d* elastic scattering for $Q^2<4$ (GeV$/c)^2$.

In order to understand the implications that this result has for the $\gamma d \rightarrow pn$ reaction, it is important to set a lower limit on the momentum transfer to the constituents in the deuteron. Ultimately, it is important to consider the momentum transferred to the individual quarks in the nucleus, since scaling is observed for deep inelastic lepton scattering from the proton, where it is believed that only one quark is struck by the incident virtual photon and no constraints are imposed on other constituents in the process. However, it is not clear theoretically how one can relate exclusive and inclusive processes without a specific quark model. Rather, we consider only the average momentum transferred to the nucleons in the $\gamma d \rightarrow pn$ process and in electron-deuteron elastic scattering. Then one can argue that the conditions for observing asymptotic scaling in these exclusive processes would be favorable when the momentum transfer to the constituent nucleons exceeds 2 (GeV$/c)^2$, since empirically this is the value where asymptotic scaling begins in electron-nucleon elastic scattering, another exclusive process. For electron-deuteron elastic scattering, consider the schematic diagram illustrated in Fig. 2(a). The square of the average momentum transferred t_N to a nucleon in the deuteron is given by

$$t_N^{ed}=(P_d'/2-P_d/2)^2 ,$$

which reduces to

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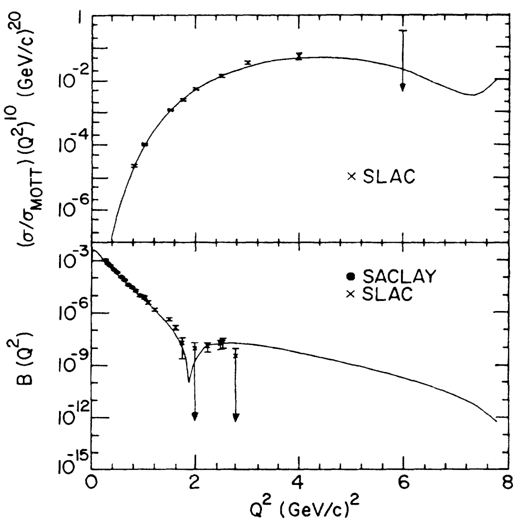

FIG. 1. Electron-deuteron elastic scattering. The data points in the upper panel are from Ref. 7, while those in the lower panel are from Ref. 8. The theoretical curves are from Ref. 9. There is no evidence for asymptotic scaling for $|Q^2|<4$ $(\text{GeV}/c)^2$.

$$t_N^{ed}=-m_d T_d/2=-(Q/2)^2 \ , \tag{1}$$

where $Q=P_e'-P_e$ is the usual four-momentum transfer for electron scattering and T_d is the kinetic energy of the scattered deuteron. In a similar fashion, the momentum transferred to a nucleon in the $\gamma d \to pn$ reaction can be

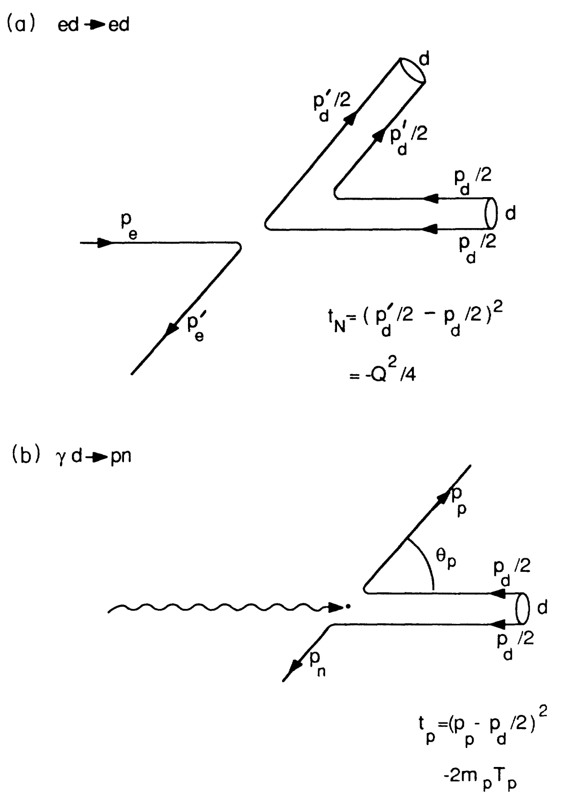

FIG. 2. Illustrations of momentum transfer to the nucleons in (a) electron-deuteron elastic scattering, and (b) photodisintegration of the deuteron.

determined by considering the diagram in Fig. 2(b). Here, the square of the momentum transferred to a nucleon is given by

$$t_N^{\gamma d}=(P_N-P_d/2)^2 \ ,$$

where P_N is the four-momentum of the recoil nucleon and P_d is the initial four-momentum of the deuteron. This reduces to

$$t_N^{\gamma d}=m_N^2+(m_d/2)^2-m_d E_N \ ,$$

where E_N is the total energy of the nucleon. With the approximation that $m_d \approx 2m_N$, then

$$t_N^{\gamma d}\approx -2m_N T_N \ ,$$

where T_N is the laboratory kinetic energy of the recoil nucleon. Perhaps the most surprising result from this analysis is the relatively large amount of momentum transferred to a nucleon in the deuteron photodisintegration process for relatively low incident photon energy compared with that from elastic electron scattering. This is illustrated in Fig. 3, where $t_N^{\gamma d}$ is given as a function of photon energy E_γ for the $\gamma d \to pn$ reaction at $\theta_{\text{c.m.}}=90°$. For comparison, the Q^2 in e-d scattering which gives the same t_N is shown on the right vertical axis. The dashed line illustrates the empirical lower limit of $Q^2=4$ $(\text{GeV}/c)^2$ or $t_N=-1$ $(\text{GeV}/c)^2$ for the onset of asymptotic scaling. This gives a lower limit of only $E_\gamma=1.1$ GeV for the incident photon energy, i.e., the available elastic electron scattering data do not give scaling information for the $\gamma d \to pn$ reaction above a photon energy of 1.1 GeV.

Recent data[10] from SLAC extend up to $E_\gamma=1.6$ GeV for the deuteron photodisintegration at $\theta_{\text{c.m.}}=90°$, giving $|t_N|=1.5$ $(\text{GeV}/c)^2$, and there is evidence for scaling above 1.4 GeV. An electron scattering experiment which

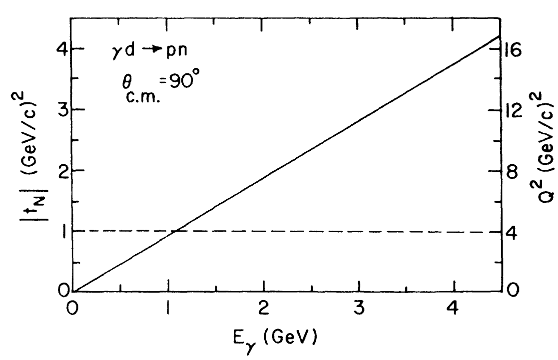

FIG. 3. The square of the four-momentum transfer to a nucleon in the $^2\text{H}(\gamma,p)n$ reaction at $\theta_{\text{c.m.}}=90°$ as a function of incident photon energy. The right vertical axis indicates the momentum transfer to a deuteron in electron-deuteron elastic scattering to yield the same momentum transfer to a nucleon as that in the $^2\text{H}(\gamma,p)n$ reaction. The dashed line indicates the $Q^2=4$ $(\text{GeV}/c)^2$ point in electron-deuteron elastic scattering and is the equivalent in momentum transfer to the constituents as absorption of a 1.1-GeV photon in the $^2\text{H}(\gamma,p)n$ process at $\theta_{\text{c.m.}}=90°$.

would give comparable momentum transfer to the nucleons would have to be performed at $Q^2=6$ (GeV/c)^2. It is believed[11] that data for the $\gamma d \rightarrow pn$ reaction can be extended up to $E_\gamma=3$ GeV at SLAC and 4 GeV at CEBAF. This latter value would give $t_N=-3.8$ (GeV/c)^2, and a comparable electron scattering experiment would have to be performed at $Q^2=15$ (GeV/c)^2. Clearly, the $\gamma d \rightarrow pn$ reaction is a powerful method for the study of asymptotic scaling in nuclei.

It is interesting to apply a similar analysis to binary photoreactions involving a nucleus in the initial and final states. The simplest binary reactions with the least power law fall off in the asymptotic region are $\gamma d \rightarrow \pi^0 d$ and $\gamma ^3\text{He} \rightarrow pd$. Since we wish to compare these reactions to the well-studied electron-deuteron elastic scattering process as well as the $\gamma d \rightarrow pn$ reaction, we consider here the momentum transfer to the deuteron in these cases. The momentum transfer to the nucleons in the recoil deuteron can be seen from Eq. (1) to be a factor of 2 lower than that to the deuteron. For the case of $\gamma d \rightarrow \pi^0 d$, the momentum transfer is given by

$$t_d = -2m_d T_d ,$$

where T_d is the outgoing kinetic energy of the deuteron. The momentum transfer t_d is given as the solid curves in Fig. 4 for $\theta_{\text{c.m.}}=45°$ and 90°.

The momentum transfer to the deuteron, t_d, for the $^3\text{He}(\gamma,d)p$ reaction is represented by the dashed curves in Fig. 4 for comparison to that of the $^2\text{H}(\gamma,d)\pi^0$ reaction. Of course, more momentum is imparted to the deuteron at a more forward reaction angle. For example, at $\theta_{\text{c.m.}}=45°$ a momentum transfer of $t_d=-4$ (GeV/c)^2 to the deuteron can be achieved with the absorption of only a 1.6-GeV photon. Proposals[11,12] at both SLAC and CEBAF exist to study these reactions in the GeV region.

In summary, it appears that photoreactions in few-body systems are an extremely promising method to search for the onset of asymptotic scaling in exclusive nuclear reactions. The main problem in previous electron scattering studies is that it is necessary to impart more than $Q^2=4$ (GeV/c)^2 to the deuteron, and this has proved impractical owing to the extremely small cross section. However, for the $^2\text{H}(\gamma,p)n$ reaction this momentum transfer to the constituents has already been exceeded[10] experimentally and it appears practical to extend the momentum transfer to the constituent nucleons to greater than 2.5 (GeV/c)^2 at SLAC and greater than 3.8 (GeV/c)^2 at CEBAF. In order to compete with this latter momentum transfer, a corresponding elastic scattering experiment would have to be performed at $Q^2 \approx 15$ (GeV/c)^2. With regard to momentum transfer to the deuteron itself, it may be possible to exceed the present limit from electron scattering by performing experiments[11,12] with the reactions $^2\text{H}(\gamma,d)\pi^0$ or $^3\text{He}(\gamma,d)\text{H}$. Unfortunately, there are no cross section data available in the GeV region to determine the practicability of these experiments. However, it is likely that these experiments could be performed for a photon energy as high as 2 GeV at CEBAF, and thus photodeuteron reactions could be studied at a higher momentum transfer to the deuteron than hitherto possible in electron-deuteron elastic scattering.

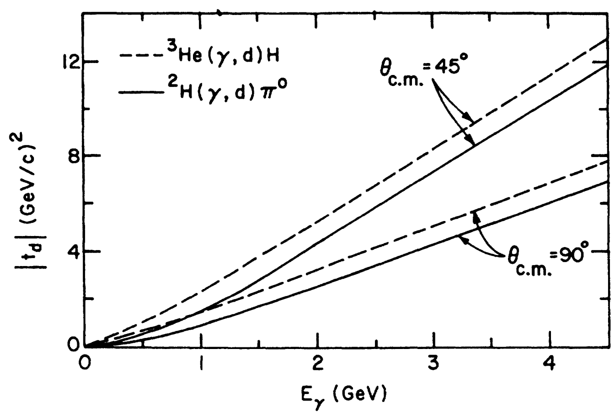

FIG. 4. The square of the four-momentum transfer to a photodeuteron in the $^3\text{He}(\gamma,d)\text{H}$ reaction (two dashed curves) and the $^2\text{H}(\gamma,d)\pi^0$ reaction (solid curves) as a function of photon energy.

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